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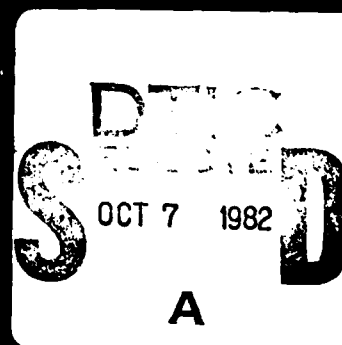
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**US Army Corps
of Engineers**

Cold Regions Research &
Engineering Laboratory

Wastewater applications in forest ecosystems

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Wastewater applications in forest ecosystems

H.L. McKim, W.E. Sopper, D. Cole, W. Nutter, D. Urie,
P. Schiess, S.N. Kerr and H. Farquhar

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Under proper design and management, a forest ecosystem in the central United States should renovate municipal wastewater as long or longer than conventional agricultural systems, especially when design limitations are hydraulic loading rate, heavy metals, P and N. Forest systems require smaller buffer zones than agricultural systems and lower sprinkler pressures. Immature forests are better wastewater renovators than mature forests.

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PREFACE

This report was prepared by Dr. Harlan L. McKim, Research Soil Scientist, Earth Sciences
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Agronomist, Memphis District, U.S. Army Corps of Engineers. The study was conducted as part of
the U.S. Army Corps of Engineers Civil Works Research Work Unit CWIS 31634, *Development of
Data to Update Manual for Land Treatment of Wastewater.*

The purpose of this report is to summarize the current state of knowledge relating to the
application of municipal wastewater in forest ecosystems and to assist in the design of such sys-
tems. This report will supplement the *Process Design Manual for Land Treatment of Municipal
Wastewater,* EM 1110-1-501.

The authors express their appreciation to Richard Thomas (U.S. Environmental Protection
Agency), Daniel Leggett and Gunars Abele (CRREL) for technical review of this report.

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INTRODUCTION

Forestland is the largest single land use in the
United States. Except for the Great Plains and
the arid Southwest, forests are abundant and well
distributed and can be found near most metropol-
itan areas where wastewaters are generated. Forests
and brushland occupy 33% of the total land area
of the United States (Table 1). In the highly pop-
ulated Northeast, forestland represents 68% of
the total land area, outranking cropland by a ratio
of 5 to 1. Even in New Jersey, the most densely
populated state, nearly half of the land area is in
forest. Most forestlands are located in rural areas,
are usually readily accessible, and have lower land
values than agricultural lands. In addition, forest-
land represents a great potential for recycling mu-
nicipal wastewater due partly to the highly per-
meable soils generally found in established forests.
Forest ecosystems are usually far removed from
the human food chain, except in some watershed
areas; consequently, public health concerns and
the social acceptability of wastewater application
to such lands may be more easily managed.

To adequately realize the forests' potential for
wastewater renovation one must recognize that
forest ecosystems behave differently than agri-
cultural systems in a number of ways. Forests
have a long term capacity for storing nutrients
as plant biomass. In contrast, agricultural systems
usually require annual harvesting. Thus, use of
forests may therefore be less costly because they
are easier to manage.

Because the forest is a stable ecosystem, it has
the capacity to receive periodic overloads of waste-
water without adverse effects either to the ecosystem
or to leachate water quality. Also, wastewater
usually can be applied over a longer period of time
in forests than on row crops. In fact, in many
parts of the country wastewater can be applied
year-round in forest ecosystems. By use of forests
in a land treatment system, a municipality may be
able to reduce initial costs by minimizing storage
requirements.

The data in this report will be presented for the
various forest regions. These are 1) Western forest
ecosystems (Douglas fir, poplar), 2) Eastern forest
ecosystems (mixed hardwoods, red pine, white
spruce, northern hardwood, poplar, others [larch,
green ash, tulip poplar, red oak, northern white
cedar]), 3) Southern yellow pine ecosystems.
This list does not suggest that the irrigation of
wastewater should be limited to the above regions
and forest types. Rather these are the forest systems
about which information of this type is available.

FOREST SYSTEMS DESIGN

The three modes of land application of waste-
water are overland flow, rapid infiltration and
slow-rate infiltration. The system most appropriate
for use in forests is slow-rate infiltration because
it provides for adequate soil/root aeration and is
compatible with the uneven surface topography
common to forests.

Table 1. Land area (million ha) of the United States by land use and region.*

Land use	Area	Proportion (%)	Region			
			North	South	Mountains	Pacific Coast
Forest land						
Commercial						
timberland	202.4	22.0	72.0	78.0	24.9	67.4
Unproductive	102.8	10.3	1.7	7.1	26.9	59.0
Reserved	7.0	0.8	1.7	0.7	3.2	1.3
Deferred	1.0	0.1	—	—	0.9	0.2
Total forest land	313.2	33.2	75.4	85.8	55.9	127.9
Cropland	172.9	18.8	105.4	42.0	15.2	10.4
All other land	441.2	48.0	73.5	79.9	153.6	134.2
Total all land	927.3	100.0	254.3	207.7	224.7	272.5

*After U.S. Forest Service (1973).

Pretreatment

In most cases only primary treatment, or less, is required before forest applications to obtain adequate renovation to drinking water standards (Cole and Schiess 1978). The degree of pretreatment necessary is only that which will facilitate pumping, sprinkler irrigation and odor control, or respond to regulatory constraints. Chlorination is not required for a number of reasons, most notably the remoteness of most forests and the fact that it produces undesirable chlorinated organics. These, along with chlorine residuals, could reduce the trees' ability to assimilate nutrients.

Distribution systems

Unlike practices frequently followed in agricultural crop irrigation, forest systems usually use a solid-set irrigation arrangement. Main and lateral lines are normally not moved because it is difficult to move pipe among the trees and virtually impossible to move piping covered with snow and ice. Most solid-set forest systems use rotating impact sprinklers for distributing the wastewater; however, a gated pipe arrangement may be preferred in situations where spray is not desirable, such as buffer areas or near access sites.

Spacing of sprinkler heads for solid-set forest systems should be somewhat closer than those for open agricultural areas because trees and leaves can interfere with the distribution pattern. Most researchers feel that an 18-m spacing between sprinklers and 24 m between laterals is preferable for wooded areas. These spacings seem to give the best tradeoff between good distribution and reasonable costs. Wider spacing between laterals usually results in lower installation costs; however,

closer spacing provides better wastewater distribution, reduces wind drift, permits lower operating pressures, and frequently results in lower operating costs. Operating pressures at the sprinkler nozzle should not exceed 0.38 MPa because of potential damage to the trees, although pressures up to a maximum of 0.59 MPa are possible with some thick-barked hardwood species. Sprinkler risers should be high enough to keep the sprinklers above the vegetation and to assure uniform distribution. Suggested riser heights are 1.0-m minimum and 1.5-m maximum (Myers 1978).

Special consideration must be given to the removal of brush, limbs, and trees along laterals during the installation and maintenance of solid-set forest systems. Sufficient forest vegetation must be removed to ensure satisfactory wastewater distribution and to permit convenient viewing of sprinkler operation. On the other hand, minimal site disturbance and the least possible exposure of mineral soil is desirable to maximize site productivity and minimize erosion potential. A reasonable balance seems to be a 1.5 to 3-m cleared path for the lateral, and a 1.5-m cleared radius around each sprinkler head. Even so, the uniformity of wastewater distribution achieved in wooded areas is frequently below acceptable agricultural standards. This is not of major concern, however, since tree root systems are usually quite extensive.

The selection of either a buried or an aboveground solid-set system is a site-specific decision. Aboveground systems are easier to install, cause minimal site disturbance, and give ready access for repair and maintenance as well as flexibility during design and operation. Buried systems, on the other hand, are more aesthetically pleasing, more permanent, less

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susceptible to vandalism, easier to operate in winter, and can facilitate forest management activities such as thinning, harvesting and regeneration.

Appreciable differences in land elevations are frequently encountered in forested areas; these make it difficult to maintain uniform distribution of wastewater over the entire irrigation site. This problem can be solved by any of three methods. First, throttling valves may be placed at the beginning of each lateral line to establish the desired pressure regardless of the elevation of the lateral within the irrigation site. Second, the lateral lines and the sprinklers may be placed closer together at the higher elevations to compensate for lower pressure. Third, a flow control device may be used at each sprinkler. The first method requires appreciable amounts of energy while in the second a greater variety of nozzle sizes and parts need to be kept on inventory. Forest plantations may be irrigated with movable sprinkler systems until tree heights interfere with sprinkler distribution. Christmas tree crops can always be irrigated with movable systems.

Wintertime forest irrigation requires special design considerations where subfreezing conditions are encountered. We recommend that two complete pumping plants be used to ensure continuous distribution of wastewater when long term freezing conditions are encountered. This is necessary to prevent wastewater from freezing in surface and shallow-buried pipes, unless the pipes are drained after use. Storage pond space is required to compensate for pumping plant down-time. However, a standby pumping system frequently will eliminate, or at least decrease, the need for storage space. Continuous year-round forest irrigation requires a smaller storage reservoir than agriculture systems because there is less down-time for harvest, planting, etc. Also, forest systems can continue in operation for longer periods during high rainfall or prolonged wet.

Trees growing under high soil moisture regimes may be subject to windthrow. Windthrow susceptibility is a function of soil moisture, exposure to wind, prevailing wind speed, soil type and rooting depth. We suggest that an unirrigated strip of trees be left on the windward side of power line rights-of-way, open fields, roads, etc., to minimize windthrow. The width of the unirrigated strip must be determined on a site-specific and species basis, but generally should not exceed 2.5 times the tree height.

PUBLIC HEALTH CONSIDERATIONS

The state-of-the-art in public health concerns during land treatment cf wastewater has been extensively discussed in a series of articles in the *Proceedings of the International Symposium on the State of Knowledge in Land Treatment of Wastewater* (McKim 1978). This document shows that public health concerns in forest systems differ from those in agricultural systems with respect to the need for buffer zones, the introduction of trace metals into the human food chain, pathogens and public access.

Buffer zone requirements

The wider buffer zones sometimes required in open agricultural systems are not necessary in most forest systems. The purpose of these buffer zones is to reduce the transmission of viruses and bacteria via aerosols produced by spray irrigation. In forest systems the production of aerosols is greatly reduced because of lower sprinkler pressures. Aerosols that are produced are generally confined within the forest and do not escape because of reduced windspeeds and the physical barrier provided by the trees (see Fig. 1, 2 and 3).

Studies at the Pack Forest in Washington State (Fritschen et al. 1970) have shown that the speed of wind blowing into the forest was reduced to an equilibrium state within 60 m of the forest edge (2 to 3 tree heights) (Fig. 1). The equilibrium speed in the tree stem space ranged from 8 to 27% of the wind speed above the canopy. The equilibrium wind speed extended to the edge of the forest when the wind was blowing from the forest out into a clearcut (Fig. 2). The equilibrium wind speed under these conditions was typically less than 10% of the reference wind speed above the canopy. The equilibrium state is defined as that condition at which the wind speed in the forest becomes independent of the wind speed above the canopy. Typically, equilibrium wind speeds range from 0.1 to 0.4 m/s.

Common equilibrium wind speeds for a deciduous coastal forest, a deciduous northern forest and a Douglas fir forest are given in Table 2. Generally the deciduous forests have lower equilibrium speeds, presumably because of the presence of understory vegetation and a denser canopy. In all three cases the basal area did not differ significantly, although the number of plants per hectare differed by a factor of more than four. This indicates that the
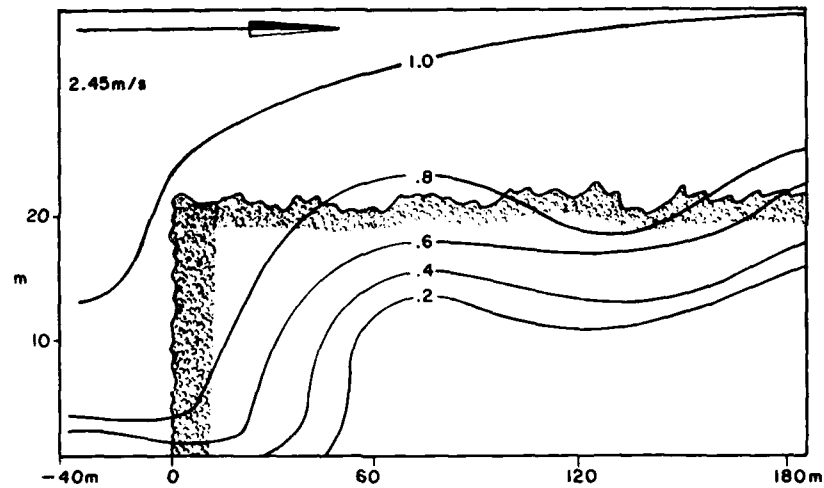
Figure 1. Vertical cross section of wind speed normalized to a reference wind speed above the canopy with wind blowing into the forest (after Fritschen et al. 1970).
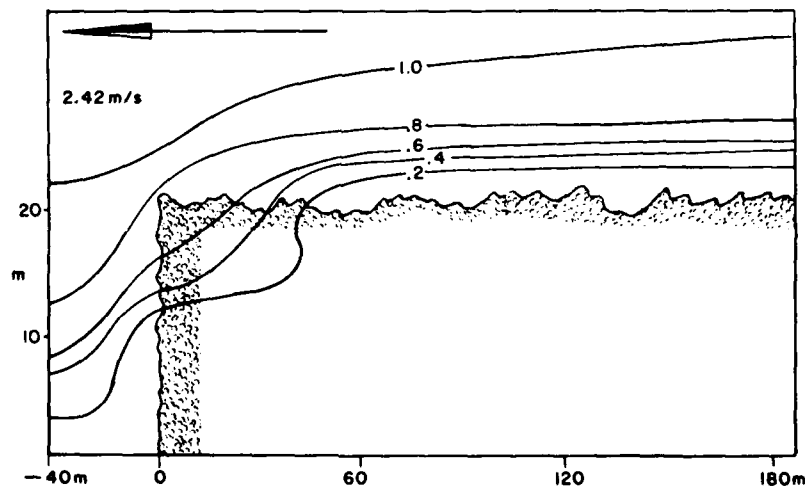
Figure 2. Vertical cross section of wind speed normalized to a reference wind speed above the canopy with wind blowing out of the forest into the open (after Fritschen et al. 1970).

•••••••••• Dense conifer with understory (Gisborne 1941)
━━━━━━ Dense hardwood jungle with understory(Latimer 1950)
━ ─ ─ ─ Moderately dense conifer stand-no understory(Fons 1940)
─ ─ ─ ─ Isolated conifer stand-no understory(Reifsnyder 1955)
──•── Dense cotton(Arizona)(Fritschen 1966)
──···── Douglas fir forest(Pack Forest 1970)
(Fritschen et al, 1970)
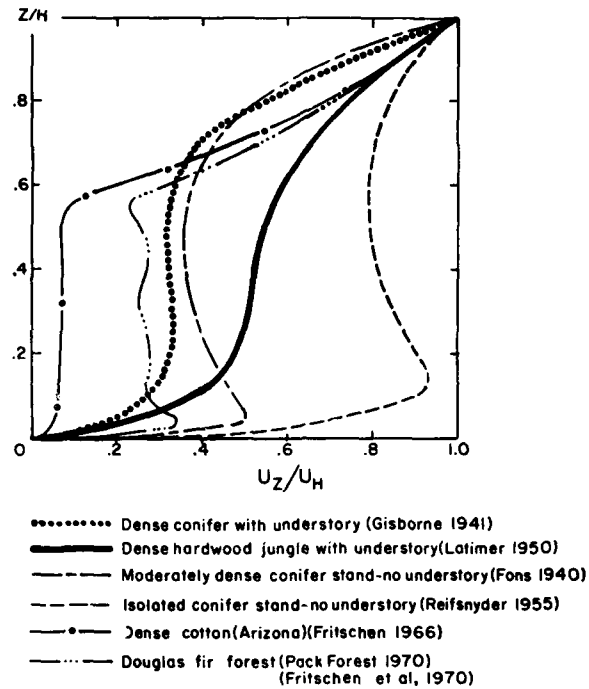
Figure 3. Comparison of normalized wind profiles of various vegetative canopies. Z is the reference height above the ground, H is the height to top of canopy, U is wind speed, U_z is the wind speed at reference height above ground and U_H is the wind speed at top of canopy.

Table 2. Equilibrium wind speed in three different forest types.

	Plants/ha	Basal area (m^2/ha)	Average DBH† (cm)	Canopy height (m)	U_{stem}/U_{top} *
Deciduous coastal forest**	652	31.4	15.1	32	0.13
Deciduous northern forest††	1,663	32.2	15.7	17	0.22
Douglas fir forest***	3,089	34.4	12.7	25	0.27

* The equilibrium wind speed is expressed as a ratio of the wind speed in the forest and a reference wind speed above the forest.
† DBH—diameter at breast height.
** Tourin and Shen (1966).
†† Shinn (1969).
*** Fritschen et al. (1970).

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Table 3. Calculated concentrations of aerosol particles as a function of distance in a Douglas fir forest and open land.

Distance from source (m)	Aerosol particle* concentration	
	Douglas fir forest† (%)	Open land** (%)
1	100	100
10	5	12
100	0.06	0.12

*Particle diameter, average 3.3 μm.
†Equilibrium wind speed in forest 0.3 m/s.
**Wind speed in the open 2.2 m/s.

basal area is a more meaningful parameter to assess wind speed reduction in a forest than stems/ha. Figure 3 shows the effect of vertical vegetation distribution on the wind speed profile. Canopies without understory showed a ground level jet typically 2–3 m above ground with speeds increasing approximately 20% over wind speeds in the upper stem space.

Aerosol particle distribution is primarily affected by atmospheric stability (which is a function of wind speed, air and surface temperature and surface roughness), time of release, and presence and density of vegetation cover (Edmonds and Driver 1974). Data from studies carried out in a Douglas fir forest showed that particles were unable to escape from the forest under a wide range of meteorological conditions (Edmonds 1971, Edmonds and Driver 1974). The factors responsible for trapping aerosols in forests are temperature inversions created in the top of the canopy, and the physical obstruction of the vegetation cover.

Data for the decrease of particle concentration as a function of distance are shown in Table 3. They were computed using a dispersion model developed by Chamberlain (1953) and modified by Edmonds and Driver (1974) which showed good agreement between computed and observed values. The data show that the concentrations dropped to 5% in the forest 10 m away from the source, as compared to 12% in the open.

The University of Southern California studied the travel of airborne bacteria by spraying settled, undisinfected sewage (California Water Pollution Control Board 1957). Coliform bacteria were tested with a membrane filter technique, using an impinger-type air sampler. All results were negative outside the detectable mist zone. The study concluded that coliform organisms were able to be airborne only in moisture droplets, and that no health hazards existed beyond the spray or mist zone. The

case with the wind blowing out of the forest (Fig. 2) will have to be considered in the design. From Figure 2 it follows that spray irrigation on the leeward side can be carried out next to the inward forest edge. Aerosol drift will usually be contained within the forest, primarily because of the greatly reduced wind speed at the level of the sprinkler.

Toxic effects

The potential for introducing harmful trace elements into the human food chain is greatly reduced in forest systems. The only exception is via free ranging wildlife, such as deer that might forage on forest vegetation, be killed and consumed by humans. While studies of this possibility are limited, it has been shown that some heavy metal concentrations increased slightly in the tissues of cottontail rabbits captured in wastewater-irrigated forests (Wood et al. 1975). The data indicated that while copper concentrations in the rabbits' kidneys increased by less than 10%, kidney cadmium concentrations decreased by more than 25%. The heavy metal levels that did increase, however, were found to be within the normal range in nature.

Public access

Public use of wastewater-irrigated forests may have to be discouraged to protect the sites from vandalism; however, hunting and other recreational activities may be allowed with proper control. This recommended limited access is not based on a potential adverse public health consideration, but on the costs associated with vandalism.

HYDRAULIC LOADING

Hydraulic loading is usually based on various aspects of the water budget, such as precipitation, evapotranspiration, infiltration, percolation and the water storage capacities of the soil (discussed in Sections 3.3.3–5 of the *Process Design Manual for Land Treatment of Municipal Wastewater* [EPA 1981]). The infiltration capacity of most forest soils greatly exceeds the combined rates of precipitation and wastewater irrigation and usually is not a limiting factor in the design of the system. The well-developed surface organic layer found in most forest soils maintains the high infiltration rate, protects the surface soil from raindrop impact, insulates and protects the soil from freezing, and provides a favorable environment for microbial and invertebrate activity that contribute to the biological renovation process. These conditions are found in well-developed forests, and it may take 3 to 10

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years to develop these desirable conditions by planting nonforested sites.

The permeability of most forest soils generally is greater than most agricultural soils because there is no tillage, little compaction by vehicles, and a highly developed structure because of microbial activity, the addition of organic matter, and the decomposition of deep penetrating root systems. Research has also shown that irrigation systems in forests can be installed on slopes (15 to 40%) greater than those recommended for agricultural systems. Forest land treatment systems are currently operating on slopes up to 40% (Sepp 1973, Nutter et al. 1978).

NUTRIENT UPTAKE AND LOADING

Introduction

The long term capacity of a forest ecosystem to adequately renovate wastewater is dependent on vegetative uptake of nutrients, soil sorption properties, rate of loading, chemical characteristics of the wastewater, climate of the area, and leachate water quality standards. Vegetative uptake is dependent on the species type, stand density, stand structure and age. In addition to the trees, nutrient uptake by the understory and ground herbaceous vegetation can also be important. This is particularly true during a new forest's establishment period. Nitrogen (N) uptake by vegetative cover and the form of N

applied are the primary factors to be considered in determining wastewater loading rates. For instance, a highly nitrified wastewater will be more difficult to renovate than a wastewater that contains organic or ammonia N because nitrate will readily leach through the soil, particularly during the dormant season when there is minimal plant uptake (Burton and Hook 1979). As in the case of agricultural soils, the sorption capacity of forest soils is the principal factor in the renovation of phosphorous (P) and trace metals.

The applicable water quality standards must be considered in relation to the loading rate. Most land treatment systems are designed to produce leachate water of drinking quality, according to the best practical treatment (BPT) regulations.

Nitrogen

A summary of the available data regarding N loading, uptake, and leachate quality for forest ecosystems is tabulated in Table 4. This information is discussed further by four regions: Western, Lake States, Eastern, and Southern.

Western forests

The major forest species occupying land suitable for wastewater applications in western Washington and Oregon is the Douglas fir. These sites are normally well drained because of the gravelly nature of the soil. The wastewater renovation capacity of a

Table 4. Regional N loading, uptake and leachate quality.

Region and forest type	Age (yr)	Application Period*	Application Rate (cm/wk)	Application Duration (yr)	N (kg/ha yr) Loading	N (kg/ha yr) Uptake Tree	N (kg/ha yr) Uptake Grass	Leachate† NO₃-N (mg/L)	Leachate† Total N (mg/L)
Douglas fir seedling	4	A	5.0	4	350	111	121	5.3	5.6
Douglas fir	50	A	5.0	3	370	–	–	0.6	0.9
Poplar (Northwest)	4	A	5.0	4	400	166	173	0.1	0.7
Poplar (Lake States)	5	GS	3.0	5	44	22	–	1.9	2.5
Poplar (Lake States)	5	GS	7.0	5	103	68	–	2.8	3.6
Red pine (Lake States)	20–25	GS	2.5	6	36	–	–	1.5	2.9
Red pine (Lake States)	20–25	GS	5.0	6	73	–	–	1.8	2.8
Red pine (Lake States)	20–25	GS	8.8	6	131	–	–	5.4	6.5
Southern mixed hardwood	45	A	7.6	5	684	–	–	8.0**	9.6**
Eastern mixed hardwood	70	GS	2.5	16	150	95	–	4.6	–
Red pine plantation	25	GS	2.5	16	150	–	–	3.8	–
White spruce/old field	8	GS	5.0	16	310	–	120	5.3	–
Eastern mixed hardwood	50	A	5.0	13	650	–	–	23.3	–
Red pine plantation	25	GS	5.0	7	310	–	–	14.2	–
Pioneer succession	1–9	GS	5.0	9	310	–	–	5.2	–

*A—annual, GS—growing season.

†Measured directly beneath the irrigated site.

**At the base of the slope where significant denitrification occurs, the level is 3.7 and 4.6 mg/L for NO₃-N and total N respectively.

Table 5. Nitrogen uptake (kg N/ha) by poplar and Douglas fir ecosystems irrigated with wastewater (after Cole and Schiess 1978).

Vegetative type	Year 1 1975	Year 2 1976	Year 3 1977	Year 4 1978
Poplar				
Tree	—	40	260	166
Grass	137	137	102	173
Total	137	177	362	339
Douglas fir seedling				
Tree	—	20	45	111
Grass	139	145	153	121
Total	139	165	198	232

Table 6. Net annual N uptake values.

Western forest ecosystems	Annual net N uptake* kg/ha yr
Poplar	300–400
Douglas fir plantation	150–250

*This value includes uptake by the trees as well as by the herbaceous plants.

newly established plantation of Douglas fir and a mature 50-year-old Douglas fir forest have been studied for the past 5 years. In addition, a young plantation of poplar has also been included. These study sites have annually received 350 to 400 kg/ha of N which has been applied year-round at the rate of 5 cm/wk. The annual uptake of N by these ecosystems is tabulated in Table 5.

With the growth of these new poplar and Douglas fir stands during this 4-year period, there has been a systematic shift in the vegetation. At the time of planting the sites were barren. Grass invaded these areas during the first year resulting in approximately 135–140 kg/ha of N uptake. During the subsequent 3 years the annual rate of uptake has increased, primarily due to the additional uptake provided by the trees. By the fourth year a decrease in the importance of the grass cover in uptake can be expected because of shading of the sites by the tree overstory. This clearly happened in the Douglas fir case. It would have occurred for poplar if they had not been extensively thinned. A greater rate of N uptake could have been achieved during the first year of irrigation if the sites were initially established with a grass cover. In the fourth year the net N uptake was 339 kg/ha yr in the poplar site and 232 kg/ha yr in the Douglas fir. Table 6

presents values for N uptake which were derived from the above data and which can be used for designing a land treatment s, .t m.

The high rate of uptake achieved by these forests has resulted in a corresponding low N concentration in soil leachate waters collected at the 180-cm depth (Fig. 4). The initial high concentration of nitrate found in the leachate from the poplar site was reduced to less than 1 mg/L within 12 months. This decrease coincides with the increase in N uptake shown in Table 5.

The capacity of a forest ecosystem to use and store the nutrients provided by wastewater irrigation is clearly demonstrated by the data in Table 7. Renovation by poplar increased from 53% during first year of irrigation to 97% in the fourth year. Renovation by Douglas fir seedlings changed from 89% during the first year to 75% in the fourth year. This case demonstrates the initial buffering capacity of forest soils (due to their organic content) until the vegetation cover fully occupies the site. The renovation under the 50-year-old Douglas fir forest changed from 84% during the first year to 92% in the third year.

Southern forests

Two general forest types exist in three primary physiographic regions in the Southeast. The forest types are mixed pine/hardwood and pine, and the physiographic regions are mountain, piedmont, and coastal plain. Each of the forest types has somewhat different N renovation characteristics in each of the provinces due to the length of growing season and soil physical properties, among other factors. For instance, denitrification will be higher in the moderately permeable, sloping soils of the mountains and piedmont than in the highly permeable, flat soils of the coastal plain. As a percentage of N applied, mountain and piedmont denitrification rates may range from 20 to 30%, depending on wastewater application rate and schedule, slopes and available carbon (C). Coastal plain rates may range from 10 to 20%, depending on the presence or absence of a restrictive soil permeability horizon, the timing of wastewater application and available C.

In a study of a southern mixed hardwood forest (80% hardwood and 20% pine) on a 30% slope with an application rate of 7.5 cm/wk (684 kg N/ha yr), approximately 60% of the applied N was accounted for by denitrification and as net tree storage. Nitrate concentration in the leachate at the base of the forested slope, where more than 50% of the denitrification takes place, was 3.7 mg/L, compared with 8.0 mg/L observed in the groundwater directly beneath the application site (Table 4).
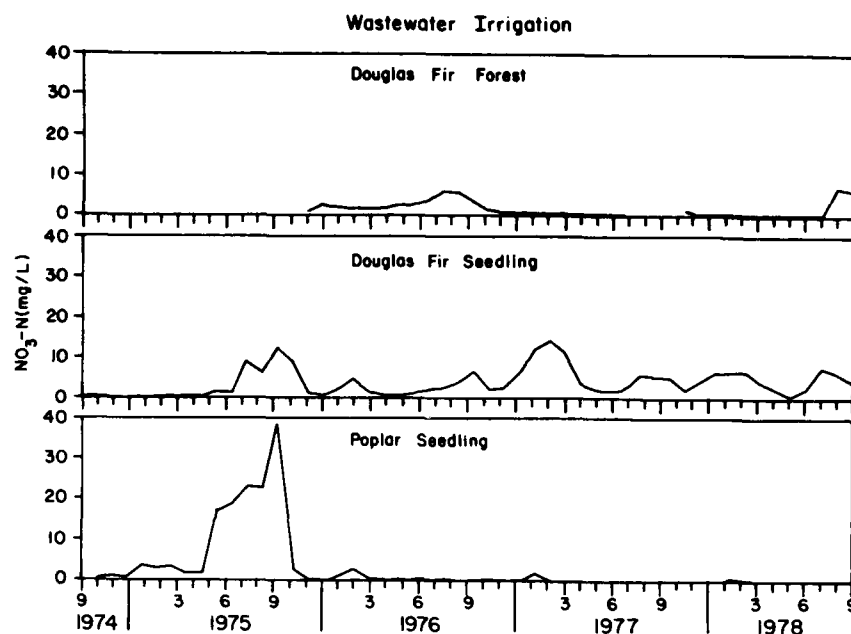
Figure 4. Nitrate-N concentration in soil solution collected at 180 cm under three different vegetation covers undergoing wastewater irrigation in western Washington.

Table 7. Total N renovation and retention capability of a gravelly Everett soil at the 180-cm depth. Young plantations of poplar and Douglas fir, and a 50-year-old Douglas fir forest growing on this soil were irrigated with wastewater.

	1975*		1976†		1977**		1978††	
	Applied (kg/ha)	Leached (%)	Applied (kg/ha)	Leached (%)	Applied (kg/ha)	Leached (%)	Applied (kg/ha)	Leached (%)
Poplar	428	47	392	6	429	3	380	3
Douglas fir seedling	428	11	320	16	349	26	341	25
Douglas fir forest (50 years)	–	~	348	16	447	3	307	8

*1975–Sept '74–August '75
†1976–Sept '75–August '76
**1977–Sept '76–August '77
††1978–Sept '77–August '78

For design purposes the net annual N storage in a vigorously growing southern mixed hardwood stand is 220 kg/ha yr, including the storage in the understory vegetation. If the stand is dense with little sunlight reaching the forest floor, the annual net storage will be reduced by 25-35%. In terms of stand management, the dominant trees should be selectively harvested at age 50 years.

No direct information is available on N uptake by southern pines irrigated with wastewater. Irrigation and fertilization studies have indicated that the maximum N accumulation rate in the tree occurs up to age 20-30 years. Although not directly comparable to wastewater irrigation, irrigation and fertilization studies indicate that a base net annual storage may be 220 to 330 kg/ha yr, figures which can be used in the design of a forest system.

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Eastern forests

During the past 16 years wastewater has been applied in several forest ecosystems at the Pennsylvania State University (Sopper and Kerr 1979). Application rates and the concentration of N in the leachate for these forest ecosystems are given in Table 8. Results from these studies provide some insight into a forest ecosystem's long term renovation efficiency. Satisfactory renovation was obtained in all forest ecosystems (eastern mixed hardwoods and red pine) where wastewater was applied during the growing season at the rate of 2.5 cm/wk, with total annual N loadings of approximately 150 kg/ha (for the period 1965-71). Renovation of nitrite-N to drinking water quality (i.e. less than 10 mg/L NO_3^--N) was satisfactory when wastewater was applied in a similar red pine plantation at a higher rate (5 cm/wk with a total annual N loading of approximately 310 kg/ha). The average annual concentration of nitrate-N in the soil leachate from 1965-1968 at the 120-cm depth steadily increased. After clearcutting the red pine plantation, successional pioneer vegetation, consisting of both herbaceous and tree species, invaded, and the nitrate-N concentration in the soil leachate decreased to an average annual value of 4.4 mg/L during 1975-1977.

The white spruce/old-field forest ecosystem has been exceptional in terms of N renovation in comparison to the other forest ecosystems. Wastewater has been applied in this area during the growing season at the rate of 5 cm/wk with excellent renovation. Average annual N loading was 310 kg/ha. During the period 1965-77, the average annual concentration of nitrate-N in soil leachate was only 7.4 mg/L. Renovation efficiency decreased slightly when wastewater applications were increased to 7.5 cm/wk over a 2-year period.

When wastewater was applied at this higher rate (annual N loading of 430 kg/ha) the average annual concentration of nitrate-N in the soil leachate increased to 12.7 mg/L. Much of the renovation efficiency of this forest ecosystem must be attributed to the dense herbaceous ground cover. Average annual dry matter production of this herbaceous cover was 6111 kg/ha, with an annual N uptake of 120 kg/ha.

The leachate water quality from year-round application of wastewater in a mixed hardwood forest at 5 cm/wk did not meet the 10 mg/L nitrate-N concentration requirement for drinking water. At 5 cm/wk the total annual N loading was 650 kg/ha and the average annual concentration of nitrate-N in soil leachate at the 120-cm depth was 23.3 mg/L. Although this exceeded the drinking water standards at the 120-cm depth, there was no adverse effect on groundwater quality. The mean annual concentration of nitrate-N in groundwater monitoring wells remained below 3.6 mg/L (Sopper and Kerr 1979).

We recommend that during design the values given in Table 9 be used for net annual N storage for the various eastern forest ecosystems.

Table 8. Mean annual concentration of nitrate-N (mg/L) in soil water at the 120-cm depth in the forest ecosystem at the Penn State project.

Year	Red pine I Hublersburg soil* 0**	Red pine I Hublersburg soil* 2.5**	Red pine II Hublersburg soil 0**	Red pine II Hublersburg soil 5**	Hardwood Hublersburg soil 0**	Hardwood Hublersburg soil 2.5**	White spruce/ old field Hublersburg soil 0**	White spruce/ old field Hublersburg soil 5**	Hardwood Morrison soil† 0**	Hardwood Morrison soil† 5**
1965	0.9††	2.2	0.9	3.9	—	0.0	0.3	8.0	—	—
1966	0.1	2.1	0.1	9.3	0.1	0.2	0.1	5.0	0.1	10.6
1967	0.9	1.7	1.8	13.8	0.3	1.4	0.3	6.1	1.4	19.2
1968	0.9	2.7	1.6	20.0	0.1	8.0	0.2	3.7	0.1	25.9
1969	0.2	4.2	0.5	24.2	0.1	7.2	0.2	2.3	0.3	23.7
1970	1.0	5.3	1.0	8.1	1.0	5.0	1.0	3.5	1.0	42.8
1971	2.6	8.3	2.6	2.1	0.5	5.8	0.5	3.8	0.8	17.6
1972	6.0	21.8††	6.0	14.5***	4.7	23.9††	3.2	11.8***	4.7	22.9
1973	0.5	13.7††	0.5	8.7***	3.0	14.7††	0.5	13.5***	1.3	17.3
1974	0.7	16.1	0.7	7.8	1.5	14.5	0.5	10.9	0.5	14.3
1975	1.3	11.9	1.3	5.1	1.7	11.6	0.8	12.9	0.8	9.0
1976	0.7	9.8	0.7	4.3	1.2	12.5	0.8	8.4	0.6	4.8
1977	0.7	5.0	0.7	3.7	1.4	9.4	0.9	6.9	1.1	5.1

*Silt loam soil
†Sandy loam
**Application rate in cm/wk.
††Application rate increased to 3.8 cm/wk.
***Application rate increased to 7.5 cm/wk.

Table 9. Annual N storage for eastern forest ecosystems.

Eastern forest ecosystem	Annual N storage* (kg/ha)
Mixed hardwoods	224
Red pine	112
White spruce/old field vegetation	280
Pioneer succession vegetation	280

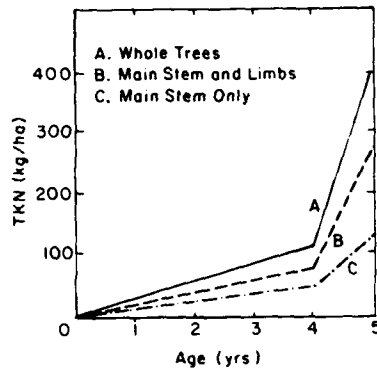*This value includes N uptake by the trees as well as herbaceous vegetation.

Figure 5. Assimilation of TKN in a plantation of "Raverdeaux" poplar, spaced 1.25 x 1.25 m, with 90% survival.

Lake state forests

In a study conducted in Michigan, a fully stocked plantation of "Raverdeaux" poplar assimilated 120 kg/ha of N during the first 4 years of wastewater irrigation (Fig. 5). An additional 290 kg/ha was assimilated during the fifth year, corresponding to the crown closure and the recycling of much of the stored N from the herbaceous understory (Fig. 5). This total (410 kg/ha) represented 80% of the N added by the 7-cm/wk application rate over the 5-year period. Leachate water quality indicated that about 20% of applied N leached beyond the root zone under the 3-cm/wk rate, while about 40% was leached during the fifth year under the 7-cm/wk rate.

Nitrogen concentration in leachate under three levels of irrigation of a red pine plantation was essentially stable after the third year of irrigation. At the highest application rate, 80-90 kg/ha yr is removed by vegetation and soil, presumably mostly by denitrification (Urie et al. 1978).

Studies at Michigan State University have illustrated the rather poor N renovative capability of mature northern hardwood forests (Neary 1974, Burton and Hook 1979). Mineral forms of N in wastewater passed through the forest ecosystems without significant reductions. Organic forms of N were reduced more effectively. These ecosystems were composed of mature hardwoods which probably had little ability to increase their growth following the advent of effluent irrigation.

The younger forest ecosystems have shown much greater capacity for N assimilation, especially during the years when herbaceous cover is present. A mean annual rate of 110 kg of N/ha should be removed by Michigan forests during the early years of growth.

Phosphorus

The amount of total P in wastewater applied to a land treatment system varies considerably but usually falls within the 6 to 10 mg/L range. Studies have shown that under these concentrations the net amount of P taken up by a poplar plantation is 34% (Cole and Schiess 1978, Urie 1979). This is a significant amount; however, even if the tree did not take up any P, the soil could remove the entire amount applied under normal wastewater application rates and proper management.

For a given soil in the southeastern piedmont, the maximum P adsorption is determined by the Langmuir isotherm for each of the identified soil horizons (Table 10). The calculation required to obtain the adsorption capacity of a soil (a sample calculation for the B2t horizon) follows:

$$\text{Bulk density (g/cm}^3) \times \text{soil horizon thickness}$$

$$(\text{cm}) \times (1 \times 10^8 \text{ cm}^2/\text{ha}) \times (\text{g P/g soil}) \times$$

$$(1 \text{ kg}/1000\text{g}) = \text{kg P/ha}$$

$$1.33 \text{ g/cm}^3 \times 63 \text{ cm} \times 1 \times 10^8 \text{ cm}^2/\text{ha} \times$$

$$1.5 \times 10^{-3} \text{ g P/g soil} \times (1 \text{ kg}/1000 \text{ g}) =$$

$$12,569 \text{ kg P/ha}$$

For the total soil thickness of 152 cm, the total annual P adsorption is 23,684 kg/ha. If the annual P loading is 250 kg/ha, the estimated site usefulness is 95 years. This is a conservative estimate because neither P uptake nor removal by the vegetation is considered, nor is the fact that laboratory measurements of maximum P adsorption are usually lower than those experienced in the field because field applications take place over a long period of time and P initially adsorbed on soil aggregate surfaces will move into the aggregate.

Table 10. Soil characteristics and annual total P adsorption for soil used in the sample calculation.

Horizon	Thickness (cm)	Bulk density (g/cm^3)	Total P adsorption (g P/g soil)	(kg/ha)
A1	3	0.98	8.5 × 10^{-4}*	250
A2	12	1.08	9.8 × 10^{-4}	1,270
B1	13	1.27	1.3 × 10^{-3}	2,146
B2t	63	1.33	1.5 × 10^{-3}	12,569
B3	30	1.31	1.2 × 10^{-3}	4,716
C	31	1.52	5.8 × 10^{-4}	2,733
Total	152			23,684

*Maximum P adsorption determined by Langmuir isotherm.

The mean annual increment of total P accumulation by hybrid poplar grown over a 5-year period in Michigan was about 15 kg/ha yr. The mean annual loading rate was 16 and 37 kg/ha for the two wastewater application rates of 3 cm/wk and 7 cm/wk. Thus the P uptake rate was essentially equal to the 3-cm/wk application rate. In a neighboring red pine plantation there was no significant increase in foliage P concentration. Increases in total P in soils under these red pine forests show that essentially all P applied in the wastewater over the first 5 years was retained in the surface 10 cm of soil (Harris 1979). Leachate quality measurements verified the removal of all added P above the 122 cm level.

All of the forest ecosystems at the Penn State project have shown a sustained capacity to remove P as the wastewater percolates through the soil. The concentration of total P in the wastewater applied varied from 2.5 to 10.5 mg/L, with an average annual loading of 95 kg P/ha. Phosphorus uptake by the foliage in the mixed hardwood forest was 9 kg/ha (9.5%). Soil analyses indicated a significant increase in P concentrations to a depth of 60 cm in a silt loam soil and to a depth of 150 cm in a sandy loam soil (Richenderfer et al. 1975). In general the concentrations of soluble P in soil leachate at the 120-cm depth remained near background control levels of 0.05 mg/L (Sopper and Kerr 1979). In the white spruce/old field ecosystem, less than 2% of the P added by growing season wastewater irrigation at 5 cm/wk during 10 years was leached. In a mixed hardwood forest with a sandy loam soil that was irrigated year-round with wastewater at 5 cm/wk, the P concentration in leachate water was somewhat higher. After 8 years of irrigation, average annual P concentrations in soil leachate at the 120-cm depth peaked at 0.39 mg/L. However, over the same period of time the total P leaching loss was less than 1.2% of the total amount added by wastewater irrigation (Sopper and Kerr 1979).

TRACE METALS

The wastewater from municipal sewage treatment plants and oxidation ponds generally does not contain high levels of trace metals (see Table 9-7 in the *Process Design Manual for Land Treatment of Municipal Wastewater* [EPA 1981]). Trees usually are not as sensitive to trace metal toxicity as are highly selected agricultural plants.

At the Penn State wastewater irrigation site, soil and vegetation samples were collected from all control and irrigated plots for trace metal analysis (Table 11). The highest wastewater application rate was 5 cm/wk. At this rate approximately 21.3 m of sewage effluent was applied during the period 1963 to 1976. In the old field/white spruce area, results of the analyses indicated that there was a statistically significant increase in Zn and Ni concentrations at all depths in the wastewater-irrigated plot. No significant change was found for concentrations of Cu, Cr, Pb, Co or Cd. It should be noted that the increases in Zn and Ni concentrations were still within the normal range found in Pennsylvania soils. Analyses of soil samples collected periodically from 1963 to 1976 indicated that there was no trend of increasing concentrations of Cr, Pb, Co, Cd and Ni. There was a slight increase in Cu and Zn concentrations in the surface 30 cm of soil; however, as stated before they were within the normal range found in Pennsylvania soils. Results of foliar analyses of predominant herbaceous vegetation indicated a slight increase in Cu concentrations on the irrigated plot. Concentrations of Zn, Cr, Pb, Co, Cd and Ni remained the same or decreased on the irrigated plot. Cadmium concentrations in the foliage of wild strawberry was 0.08 mg/L in the wastewater-irrigated plot in comparison to 0.21 mg/L in the unirrigated plot. This decrease in concentration is attributed to biological dilution due to the greater biomass production resulting from the wastewater irrigation (Sopper and Kerr 1978).

In general it was concluded that spray irrigation of treated wastewater from the Pennsylvania State University sewage treatment plant did not significantly increase the heavy metal concentrations in the soil or vegetation over a 14-year period. However, it should be noted that the raw waste treated

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Table 11. Extractable trace metal concentrations (μg/g) in the surface 30 cm of soil in the Penn State white spruce/old field forest ecosystem irrigated with municipal wastewater (after Sopper and Kerr 1978).

Year	Cu	Zn	Cr	Pb	Co	Cd	Ni
Irrigated*							
1963	0.65 C†	3.23 B	0.09 A	4.61 A	1.80 C	0.04 A	0.56 B
1965	0.95 BC	3.78 B	0.06 A	4.21 A	2.75 B	0.04 A	0.67 AB
1967	1.43 A	6.15 AB	0.04 A	4.45 A	3.21 AB	0.07 A	0.89 A
1971	1.23 AB	6.01 AB	0.07 A	4.19 A	3.73 A	0.05 A	0.54 B
1976	1.92 D	7.48 A	0.01 A	3.29 A	1.87 C	0.03 A	0.73 AB
Control							
1962	0.93 AB	2.45 A	0.07 A	2.99 A	1.23 A	0.05 A	0.31 A
1965	0.66 B	2.63 A	0.08 A	3.76 A	2.12 A	0.05 A	0.28 A
1967	1.16 A	1.93 A	0.08 A	3.66 A	1.81 A	0.03 A	0.30 A
1971	0.92 AB	3.91 A	0.10 A	3.69 A	1.43 A	0.06 A	0.35 A
1976	2.49 C	2.85 A	0.10 A	3.75 A	0.70 A	0.07 A	0.88 A

*Application rate was 5 cm/wk during the growing season.
†Means followed by same letter are not significantly different from each other at the 0.05 level of significance.

Table 12. Foliar trace metal concentrations (μg/g) in selected species in the Penn State white spruce/old field forest ecosystem irrigated during the growing season with municipal wastewater (after Sopper and Kerr 1978).

Weekly irrigation amount (cm)	Cu	Zn	Cr	Pb	Co	Cd	Ni
White spruce							
0	3.31 A*	70.66 A	0.91 A	4.10 A	2.82 A	0.172 A	6.89 A
5	3.39 A	22.40 B	0.85 A	3.11 A	2.50 A	0.089 A	2.91 B
Goldenrod							
0	9.71 A	85.96 A	1.33 A	6.16 A	2.68 A	0.676 A	4.70 A
5	12.98 B	35.24 B	1.04 A	7.25 A	2.17 B	0.148 B	3.00 B
Wild strawberry							
0	5.30 A	41.36 A	0.95 A	7.89 A	3.67 A	0.212 A	5.70 A
5	7.39 B	35.66 A	1.12 A	7.64 A	3.20 A	0.076 B	3.68 B

*Means followed by same letter are not significantly different from each other at the 0.05 level of significance.

at the plant comes primarily from domestic sources. If wastewater from sources other than domestic is to be applied on the land, proper management and careful monitoring are essential to avoid toxicity problems and hazards to the food chain.

Sopper and Kardos (1973) reported declines in red pine diameter and height growth after 6 years of wastewater irrigation. Boron toxicity was suspected since other investigators (Stone and Baird 1956) had previously reported that applications of 1.2 kg of B per hectare were sufficient to induce toxicity symptoms. However, foliar analysis indicated that there was no statistically significant difference between B concentrations in the needles

on the irrigated (33 μg/g) and control (23 μg/g) trees. The average B concentration in the wastewater applied was 0.37 mg/L, resulting in an annual application of 4.5 kg of B/ha. Concentration of B in the soil leachate at the 120-cm depth was only 0.03 mg/L, indicating 92% removal by the soil/vegetation complex.

Trace metal concentrations in the vegetative cover of the irrigated forest were usually lower than in the unirrigated forest (Table 12 and 13) and were well below the suggested tolerance levels reported by Melsted (1973). Similar results have been reported by Cooley (1978a). However, he reported that wastewater irrigation did significantly increase

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Table 13. Average foliar nutrient (%) and trace metal concentrations (μg/g) in 5-year-old seedlings irrigated with sewage-oxidation-pond wastewater.

Weekly irrigation rate (cm)	Nutrient			Trace metal			
	TKN	P	K	Zn	Cu	Mn	B
"Raverdeaux" poplar							
0	1.90 a*	0.20 a	1.43 a	123 a	10 a	135 a	79 a
3	2.33 b	0.34 b	1.92 a	88 a	11 a	150 a	156 b
7	2.29 b	0.34 b	2.30 a	142 a	8 a	135 a	211 c
Hybrid aspen							
0	2.25 a	0.25 a	0.68 a	207 a	10 a	174 a	72 a
3	1.92 a	0.30 a	0.97 a	167 b	8 a	142 b	152 b
7	2.24 a	0.31 a	1.22 a	88 c	8 a	71 c	154 b
Green ash							
0	1.81 a	0.20 a	0.78 a	19 a	12 a	39 a	24 a
3	1.96 a	0.28 b	1.53 b	22 a	14 a	43 a	42 b
7	2.10 a	0.35 b	1.41 b	27 a	10 a	40 a	36 b
Northern white cedar							
0	1.55 a	0.23 a	0.55 a	37 a	5 a	146 a	23 a
3	1.60 a	0.22 a	0.75 a	28 b	5 a	98 b	54 b
7	1.57 a	0.24 a	0.67 a	30 b	5 a	59 c	45 b

*Means followed by the same letter are not significantly different from each other, within species, at the 0.05 level of significance.

foliar B concentrations in five of eight tree species tested, yet there were no visible B toxicity symptoms. On sandy soils in Michigan concentrations of B in the leachate at the 120-cm depth have equaled that of the wastewater applied, which suggests that much of the B applied on sandy soils is leached to the groundwater (Urie et al. 1978).

DESIGN CONSIDERATIONS

The steps taken in designing a slow-rate infiltration system using a forest as the vegetative cover are identical to the steps and examples explained in Appendix A of the *Process Design Manual for Land Treatment of Municipal Wastewater* (EPA 1981), with the exception of the determination of the design precipitation.

Basically, the calculation is an iterative process where the land area is first calculated, based on hydraulic loading rates, wastewater flow to be treated, and the specific soil characteristics. In a second step the land area is calculated from N loading rates and an N mass balance.

Hydraulic loading rates

The hydraulic loading rate is determined from the water balance which includes precipitation, irrigation, infiltration, evapotranspiration, soil storage and subsoil permeability. The water balance equation can be calculated on a weekly, monthly or annual basis. Information found in Section 4.5.1 of the *Process Design Manual for Land Treatment of Municipal Wastewater* (EPA 1981) is applicable. When the hydraulic loading rates are considered, design precipitation should be based on a 10-year return period frequency analysis. Potential evapotranspiration is used because it is assumed that irrigation will be sufficient to maintain evapotranspiration at the potential rate.

Nitrogen loading rates

Nitrogen management in a slow-rate infiltration system depends on vegetation uptake, denitrification and some soil storage. Nitrogen uptake rates continually change from year to year in forests in direct relation to the buildup and accumulation of biomass. This is in contrast to agricultural systems where the crops are harvested annually so that the N uptake rate for a given species is constant from year to year. Typically, growth and N uptake rates will increase from one year to the next in the early part of the life of a forest until they reach a maximum; then they begin to level off. This deflection point is dependent on the tree species, but generally, faster growing trees reach this point earlier. The

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objective of forest management is, therefore, to maintain the forest in the state of maximum growth and N uptake.

For design calculations average uptake rates should be used that are typical for the forest and its tree species (see previous section on nutrient uptake, and N and P loading). The value for denitrification varies from 10–40% of the N loading rate. A value of 15% is considered to be the minimum value that should be used when designing forest land treatment systems.

FOREST MANAGEMENT OPTIONS

The primary objective of applying wastewater to forests is to renovate the wastewater for groundwater recharge. Research has shown that a variety of management techniques can be employed to accomplish this goal. We have evaluated the following forest management options and found them to be successful.

Reforestation

Wastewater irrigation can be used very effectively to establish forests on barren land, abandoned farmland and clearcut areas. The wastewater supplies both the water and nutrients usually required for optimal survival and rapid growth of tree seedlings. Wastewater application usually will also stimulate growth of the herbaceous vegetation.
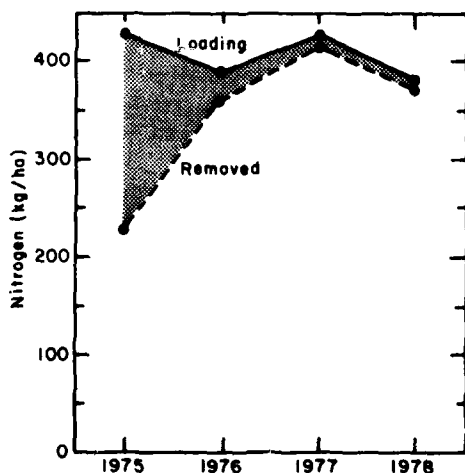
This vegetation may compete with tree seedlings and require some type of cultural treatment for control; however, the herbaceous vegetation cover is necessary during the early years of forest establishment to achieve satisfactory wastewater renovation. For example, poplar cuttings established at Pack Forest (Table 7) without a herbaceous ground cover did not renovate the applied wastewater sufficiently during the first year (i.e. 47% of total N was leached). However, by the end of the second year, with the development of a herbaceous cover, satisfactory renovation was achieved (Fig. 6).

Similarly, removal of the herbaceous cover in a 3-year-old poplar plantation in Michigan resulted in an immediate increase in nitrate in the soil leachate (Urie et al. 1978). With regrowth of the herbaceous vegetation, nitrate concentration in soil leachate decreased to an acceptable level (Fig. 7).

In Pennsylvania the interrelationship between the wastewater application rate, the type of vegetation, and the system of management has been dramatically illustrated by the conversion of an older red pine plantation to a stand of young trees and pioneer species of herbaceous vegetation (Sopper and Kerr 1978). After applying wastewater to a 25-year-old red pine plantation for 5 years at a rate of 5 cm/wk during the growing season, nitrate-N concentrations in soil leachate exceeded drinking water standards and renovation of wastewater was

Figure 6. Nitrogen loading and net N removed during the initial 4 years following the establishment of a poplar plantation (after Cole and Schiess 1978).
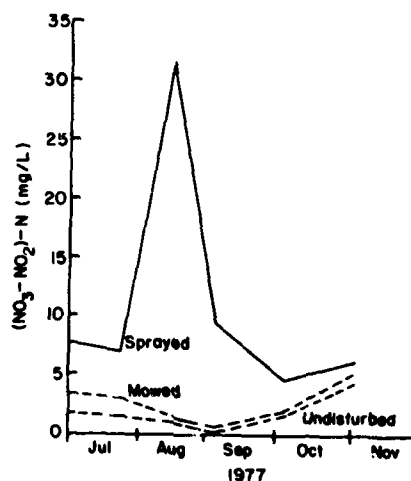

Figure 7. Nitrate in groundwater under irrigated plots sprayed to eliminate grass and weeds, mowed periodically or left undisturbed.
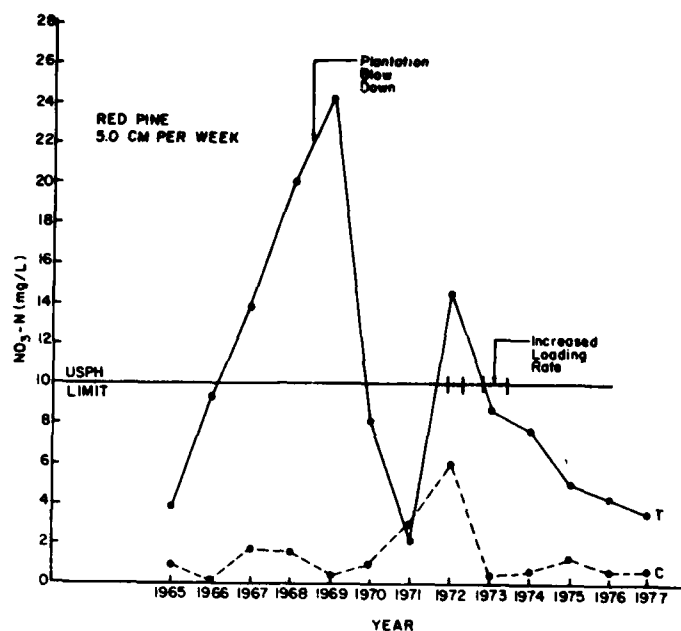
15

Figure 8. Average annual nitrate-N concentration in soil water at the 120-cm soil depth in the Penn State red pine forest ecosystem irrigated with municipal wastewater at 5.0 cm/wk during the growing season for the period 1965 to 1977.

unsatisfactory (Table 8). After 5 years, the nitrate-N concentration of leachate peaked at 24.2 mg/L. At this time (1969) the red pine plantation was clearcut following a blowdown, and a dense cover of herbaceous and shrub vegetation developed. The renovation efficiency of the site was quickly restored by the new pioneer vegetative cover. Nitrate-N concentrations in leachate water decreased to 8.1 mg/L the first year and decreased further to 3.7 mg/L during the ensuing 7 years as the new ecosystem developed (Fig. 8, Table 8).

Existing forest ecosystems

Intensive forest management practices should be carried out in forest ecosystems receiving wastewater applications. In general the objective of intensive management is to maximize fiber or biomass production and to concentrate it on the smallest number of trees per hectare without too much reduction in growth from the potential total annual growth rate. Management practices used in commercially fertilized stands would be applicable to effluent-irrigated forest sites. These management practices should allow for a compromise between fully realizing a site's potential growth rate (which would mean a high number of stems per hectare) and the need to operate equipment efficiently in the stand (logging equipment, irrigation equipment). Generally, the freedom of operation increases with a decreasing number of trees. These operations will help to keep forest renovation efficiency at a high level. The concept of "whole tree harvesting" (where the total aboveground biomass would be removed from the site) should be evaluated. For instance, harvesting 5-year-old poplar trees, including leaves, removed 100% of aboveground accumulated N, whereas harvesting of main stems would remove only 30% (Cooley 1978a).

The effect of long term storage potential is shown in Figure 9. Accumulation of total N, as measured in an undisturbed Douglas fir forest, takes place in three compartments above ground: the forest floor, the understory vegetation and the foliage of trees. The accumulation of N in the foliage reaches a steady-state condition with crown closure. At that point N accumulation in the understory vegetation actually starts to decrease; however, in the early growth phases of the stand the understory vegetation plays an important role in N accumulation. Accumulation of N by the forest floor continues throughout the first 80-100 years of stand development. Research to date indicates that this accumulated N is immobilized and not readily available to the trees.
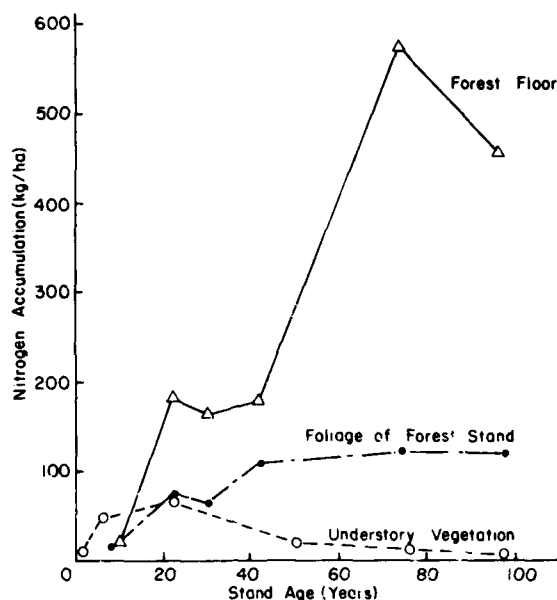
16

Figure 9. Accumulation of total N in an undisturbed Douglas-fir forest in the three compartments: 1) forest floor, 2) understory vegetation, and 3) foliage of forest stand (after Cole et al. 1975).

A possibly very effective forest management option which should be considered is the concept of slash or controlled fires to prevent nutrient leaching from the N-rich forest floor that eventually could reach the groundwater. These techniques are currently being used in the southeastern pine forests as well as the western forests to reduce fuel accumulation and to prepare sites for planting after harvesting.

Slash burning is typically carried out after harvesting throughout the Northwest. It prepares the site for reforestation by burning away the slash as well as part of the organic surface layer. In the process most i the organic N stored in the forest floor is volatilized. The combination of harvesting followed by slash burning would effectively remove close to 100% of the accumulated N in the forest floor, forest stand foliage and understory vegetation (Fig. 9).

This approach of using fire to reduce the organic accumulation has, in fact, been used at the Pack Forest wastewater spray irrigation site. The test area, previously occupied by a 40-year-old Douglas fir forest, was clearcut, followed by slash burning that removed most of the organic accumulation. The Douglas fir seedlings and

poplar cuttings were then planted in the mineral soil. This approach, however, has a trade-off that should be considered by the designer. By removing most of the organic layer through burning, some of the initial buffering capacity against N leaching is temporarily lost. Nitrate concentration under the poplar and Douglas-fir seedling plots had high initial values. On the other hand, effluent applied to a 50-year-old forest with a well developed organic forest floor showed small initial nitrate concentrations in leachate entering the groundwater. However, as the data from Figure 9 suggest, the forest will build up the forest floor and with it the capacity to buffer N leaching.

Coupled with increased growth, irrigation of trees with municipal wastewater also affects the anatomical and physical properties of wood fibers. Studies have been conducted which report that alterations of the wood fibers of red pine, red oak and aspen resulting from wastewater irrigation enhanced the value of the fiber as a raw material for pulp and paper (Murphey et al. 1973a, b; Murphey and Bowier 1975). Although the accelerated growth generally results in reduced specific gravity and wood density, lumber cut from irrigated trees can still be used for most general structural purposes.

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Short term rotation plantations

Short term rotation forestry involving irrigation and fertilization of fast growing species for wood fiber and/or fuel appears to be suited to wastewater use and renovation. Limited studies have shown that sycamore, cottonwood, poplar and sweetgum can use large amounts of N and P. For example, at the end of 3 years, poplar cuttings in the Northwest were found to remove 260 kg N/ha yr (Cole and Schiess 1978). At the end of 5 years, hybrid cottonwoods in Michigan removed up to 200 kg N/ha yr (Cooley 1978a). Biomass production has been shown to double under wastewater irrigation. Harvesting every 5 to 8 years will provide better than 80% removal of the N stored in the aboveground biomass. Consequently, satisfactory wastewater renovation can be achieved with short-rotation hardwood forest systems, often equal to annually harvested agriculture systems.

POTENTIAL LONG TERM EFFECTS ON FOREST ECOSYSTEMS

Longevity of forest systems

The factors affecting the longevity of a forest ecosystem receiving wastewater include the physical, chemical and hydrologic properties of the soil, the type of forest management, the application rate, and the capacity of the vegetative cover to accumulate and recycle the constituents in the wastewater. The longevity of a forest ecosystem which renovates wastewater unfortunately has not been fully established. The longest comprehensive study of forest ecosystems receiving treated municipal wastewater has been conducted at the Pennsylvania State University (Sopper and Kerr 1978) where the land treatment system has been operating for 16 years. In Europe Polish investigators have reported on the use of wastewater irrigation in forests for a period of 9 years (Bialkiewicz 1978). The more recent studies of forest ecosystems discussed earlier in this report have ranged from 2 to 6 years (Cole and Schiess 1978, Nutter et al. 1978, Urie et al. 1978, Burton and Hook 1979). Based upon the current information available from this limited number of studies, a properly designed and managed forest land treatment system can be expected to satisfactorily renovate wastewater longer than a conventional wastewater treatment facility. The vegetative cover can be managed so that the longevity of the forest will only be limited by the assimilative capacity of the soil.

The primary mechanisms for P removal are precipitation and adsorption, with P accumulating in soils (see *Nutrient Uptake* section). The P adsorption capacity of the soil is reduced by the annual accumulation rate, at least on a short term basis. The ratio of the annual P application rate to the soils' adsorptive capacity provides a conservative estimate of the longevity of the land treatment site.

Phosphorus adsorptive capacities have been evaluated for the forest soils in the Pennsylvania State University project. Analysis of the upper 1.5 m of the Hublersburg clay loam soal (Typic Hapludalf) indicated that the adsorptive capacity of the soil is sufficient to accept wastewater applications at approximately 150 cm/yr for more than 100 years (Sopper and Kerr, pers. comm.). Similarly, Nutter (pers. comm.) has found that the P adsorption capacity of the upper 150 cm of a Cecil sandy loam (Typic Hapludult) and a Hayesville sandy clay (Typic Hapludult) soil is sufficient to accept wastewater applications at the rate of 330 cm/yr for over 100 years.

In the Pacific Northwest, Cole (pers. comm.) has reported that after 5 years of wastewater irrigation with a total application of 450 kg/ha of total P, leachate analyses indicate that the applied P is retained in the top 10 cm of the Everett gravelly loamy sand soil (Typic Haplorthod). Less than 0.2% of the applied P remained in the leachate at the 120-cm depth. Similarly, Harris (1979) has reported retention of applied P in the surface 10 cm of a Michigan sandy soil after 5 years of application of oxidation pond wastewater at 45 to 160 cm/yr. This study is continuing, and it is estimated that the P retention capacity of the soil will be maintained for over 100 years.

The range in concentrations of trace metals normally found in typical domestic wastewater is given in Table 2-2 in the *Process Design Manual for Land Treatment of Municipal Wastewater* (EPA 1981). Research results from the Pennsylvania State University Project indicate that after 14 years of spray irrigation with wastewater in a forest ecosystem, there was a slight increase in extractable Cu and Zn concentrations in the 0 to 30-cm soil depth (Table 11) (Sopper and Kerr, pers. comm.). However, these increased levels were still within the normal range found in Pennsylvania soils.

Consequences of overloading

A forest ecosystem has a demonstrated capacity to accept temporary overloading from wastewater irrigation. This is due in part to the resiliency of forest vegetation when confronted with dramatic changes in environmental conditions. The

productivity of a forest will not be adversely affected as long as aeration remains adequate. The major detrimental effect of overloading will be a temporary impairment of the quality of the leachate water. Recovery by a forest ecosystem following chronic applications of wastewater has been found to be fastest if wastewater applications are temporarily stopped. A longer time is required for recovery if wastewater applications are continued at a reduced rate (Sopper and Kerr 1978).

Soil chemical, physical and hydrologic properties

Ongoing research has shown that soil organic matter, and earthworm and microbiological activity have increased while bulk density has decreased under forest land treatment systems. Infiltration capacity and permeability, although not significantly increased under established forest stands, are maintained at high levels. Organic layers (both litter and humus) may be reduced as the biological decomposition rate increases, particularly under high N loadings (Richenderfer and Sopper 1979). The potential exists for erosion and decreased infiltration with a decrease in organic matter. However, maintenance of high biomass production (leaf-fall) will protect the soil from raindrop impact. No reductions in infiltration capacities which might lead to reduced irrigation rates, overland flow and increased erosion have emerged from studies so far.

Despite reported increases in Na concentration in soil, no reductions in soil permeability or in soil aggregate stability have been reported in the humid forest zones. If forests are established on semiarid lands, adequate soil flushing with amounts of water exceeding evapotranspirational demands should be part of the design to prevent salt buildup in the irrigated soils.

Soil pH in the normally acid forest soils tends to be increased by the application of wastewater. With time the soil pH will be maintained at or near the pH of the wastewater. The time required to affect a change in pH is a function of the soils' buffering capacity. Increased pH will lead to a slight increase in the cation exchange capacity as will increased organic matter. The expanded presence of Na and NH_3 within the soil leads to greater leaching of cations such as Ca, K and Mg.

Productivity

It has been clear in nearly every study dealing with wastewater application to forest ecosystems that trees will increase in diameter and height, resulting in an increase in the total biomass. There are exceptions to this generalization. For example,

wastewater application in mature forest ecosystems on good sites may not result in increased productivity. As has been previously discussed in the section on nutrient uptake and loading, the greatest opportunity to increase forest productivity with wastewater application lies with species having a high growth potential that are gowing on poor quality sites. The greatest responses can be expected from immature forest stands.

Examples of forest ecosystem growth responses to wastewater applications for various forest regions are discussed below.

Western ecosystems

Increased tree production has been studied for two species, Douglas fir and poplar, as a part of the University of Washington program at Pack Forest. At this study site wastewater has been applied at the rate of 5 cm/wk on a year-round basis. After 4 years of such application (resulting in the addition of approximately 1600 kg/ha of total N), a significant increase in growth of these two species has been noted (Table 14).

These increases in tree height and diameter also result in corresponding increases in aboveground biomass production for these two species (Table 15).

Table 14. Height and diameter growth of Douglas fir and poplar receiving wastewater and riverwater irrigation.

	Diameter (cm)	Height (m)
Poplar		
5 cm wastewater	8.4	6.0
5 cm riverwater	2.7	3.1
Douglas fir		
5 cm wastewater	5.3	2.4
5 cm riverwater	3.0	1.7

Table 15. Increase in production because of wastewater irrigation (average for ages 3 and 4 years).

Plot	Production (tons/ha) Wastewater	Riverwater	Increase (%)
Poplar			
Tree	21.5	1.5	1333
Grass	8.0	1.6	400
Total	29.5	3.1	852
Douglas fir			
Tree	9.2	2.7	241
Grass	7.6	1.5	407
Total	16.8	4.2	300

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Eastern ecosystems—Pennsylvania

Treated municipal wastewater has been used for irrigation in several forest ecosystems since 1963. Application rates have varied from 2.5 to 10 cm/wk over various lengths of time, ranging from the growing season only to year-round. Tree growth responses to the wastewater application are given in Table 16. Wastewater irrigation significantly increased the diameter growth of all species, except red pine, at the high application rate (5 cm/wk). The greatest growth response was exhibited by white spruce. After 16 years of wastewater irrigation, the average diameter of the white spruce trees was 20 cm in comparison to 10 cm in the unirrigated forest, and the average height was 9.1 m compared to 4.6 m for the control trees.

Table 16. Average annual diameter and terminal height growth in Penn State forest ecosystems irrigated with wastewater (after Sopper 1975).

Species	Weekly Irrigation amount (cm)	Avg. diam. growth (mm)	Avg. terminal ht. growth (cm)
Red pine	0	1.5	42
	2.5	4.3	58
	5.0	1.5	49
White spruce	0	4.5	25
	5.0	10.0	60
Red maple	0	2.6	—
	2.5	13.0	—
Sugar maple	0	2.6	—
	2.5	13.0	—
Oaks	0	4.1	--
	2.5	4.8	—
	5.0	6.0	—

Table 17. Five-year total height growth (m) of tree seedlings on the Penn State project (after Kerr, pers. comm.).

species	Total height Irrigated	Control
European larch	2.1	—*
Japanese larch	2.0	—*
White pine	1.6	0.6
Red pine	0.9	0.5
White spruce	0.9	0.7
Pitch pine	0.9	0.3
Austrian pine	0.8	0.6
Norway spruce	0.7	0.4

*No trees of these species survived on the control plots.

Eight tree species were also planted in an old-field area to determine which species might be best suited for sites to be used as treatment areas. One- and two-year-old seedlings of European larch (*Larix decidua*), Japanese larch (*Larix leptolepis*), white pine (*Pinus strobus*), red pine, white spruce, pitch pine (*Pinus rigida*), Austrian pine *(Pinus nigra)* and Norway spruce (*Picea abies*) were planted, with some plots irrigated with 5 cm of effluent per week and some plots maintained as a control. First-year survival on the irrigated plot was 88% and 52% on the control plot. The total height growth of surviving seedlings at the end of 5 years is shown in Table 17.

Lake states ecosystems—Michigan

Seedlings and hybrid-poplar cuttings were irrigated over a 5-year period in Michigan using the wastewater from a municipal oxidation-pond sewage treatment system. The trees were irrigated 18–21 wk/yr, receiving 3 and 7 cm of wastewater on one day per week during the growing season. Hybrid poplars and white cedar showed significant increases in height growth and survival (Cooley 1978b). All species showed increased mean growth under sewage irrigation although there was no significant growth difference between the two irrigation rates (Table 18).

A 20- to 25-year old red pine plantation was irrigated over five growing seasons in Michigan using oxidation pond wastewater. No measureable changes in height or diameter growth occurred under growing season irrigation at rates of 2.5, 5 and 8.8 cm/wk (Cooley 1979).

Growth response of tree species irrigated with municipal wastewater has been reported for Polish sandy forest soils as listed in Table 19 (Bialkiewicz 1978).

These results indicate that under proper design and management a forest ecosystem should renovate wastewater as long or longer than agricultural systems, especially when the design limitations are hydraulic loading rate, heavy metals, P and N.

SUMMARY

Over the last 10 years there has been an extensive amount of research conducted on the use of forests in renovating municipal wastewater. The results from throughout the central states indicate that under proper design and management a forest ecosystem should renovate municipal wastewater as long or longer than conventional agriculture systems. This is especially the case when the design limitations are hydraulic loading rate, heavy metals, P and N.

The wider buffer zones usually required in open agricultural systems are not necessary in most forest

Table 18. Height growth and total dry tree weight of
irrigated forest plantations, Middleville, Michigan
(after Cooley 1978b).

Species	No. years irrigated	Height growth (cm)			Total dry weight (kg/ha)		
		0*	3*	7*	0*	3*	7*
Poplar hybrids							
1	4	180	440	540	470	10,200	18,630
2	5	380	640	620	15,500	61,200	58,000
3	5	300	350	440	5,980	12,100	20,010
Green ash	5	160	260	220	2,552	9,114	5,900
European larch	5	130	190	260	120	670	1,390
Japanese larch	5	180	250	330	3,312	6,240	6,400
Tulip poplar	5	160	250	240	390	3,900	4,050
Red oak	5	60	110	100	510	540	970
Northern white cedar	5	30	60	100	620	1,500	740

*Irrigation rate (cm/wk)

Table 19. Growth response of tree
species (after Bialkiewicz 1978).

Species	Increase in volume growth over controls (%)
Scotch pine	135
European larch	197
Basket willow	385

systems. Since the buffer zone's purpose is to re-
duce the transmission of viruses and bacteria via
aerosols produced by spray irrigation, lower sprink-
ler pressures, the generally confined areal distribu-
tion in forests, and the physical barrier provided
by the trees greatly reduce the size of the buffer
zone.

It has been clearly shown in almost all studies
dealing with wastewater application to forest eco-
systems that immature trees will increase signifi-
cantly in diameter and height which in turn results
in an increasing total biomass. However, when
wastewater is applied to mature forest ecosystems
on good sites, productivity is not noticeably in-
creased.

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